Design Notes

"Switch mode power supplies" – words that may irrationally strike fear and terror into the hearts of radio amateurs because of the potential for interference and noise these PSUs can generate. But SMPSUs can be cleaned up and, used with proper filtering and screening, can be made as quiet as needed – versatile and useful, as well as being cheaper, lighter and more readily available than linear PSUs.

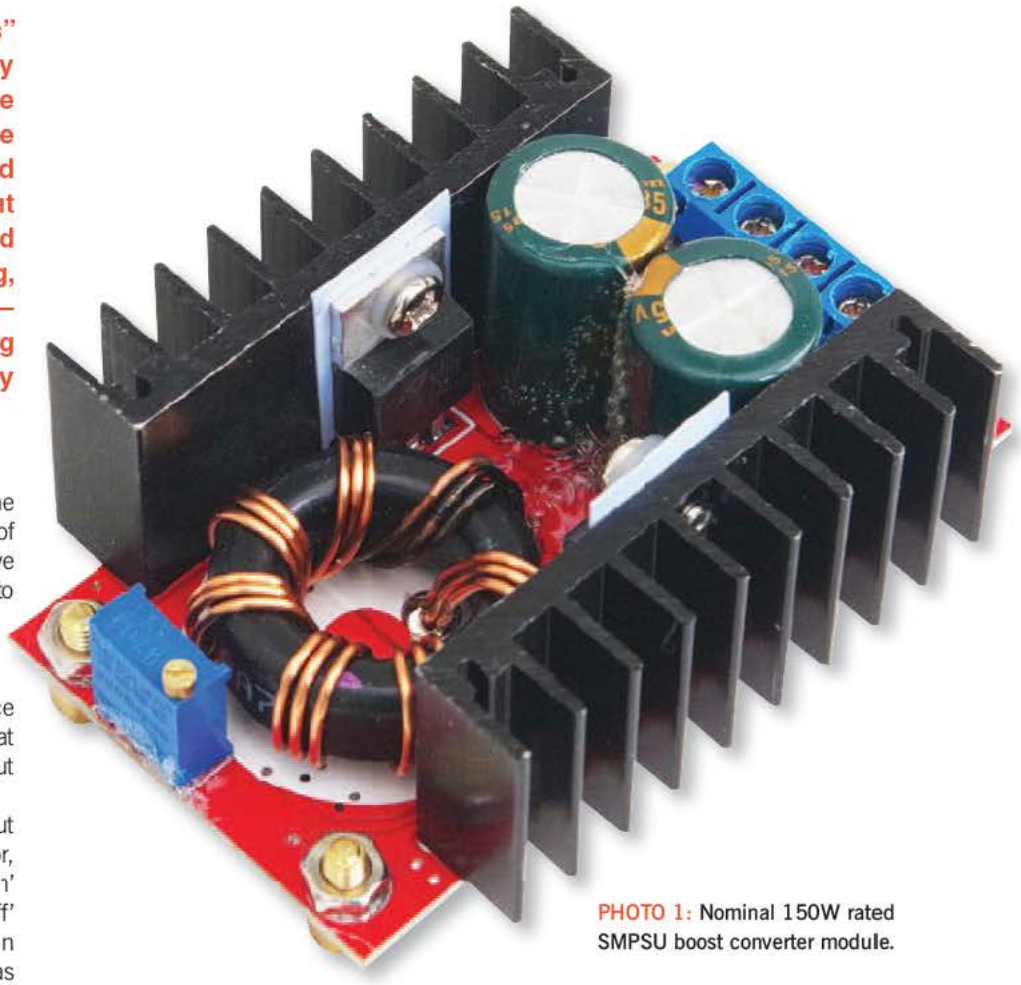

PHOTO 1: Nominal 150W rated SMPSU boost converter module.

Here we're going to have a quick look at the basics of SMPSU design to get an outline of how they work. By understanding this, we can go a long way to see why and how to make them clean and interference free and adapt for our own purposes, or make our own. We'll also look at a couple of low cost modules from a popular e-commerce site. We'll start by considering just those that take a DC input directly. We'll worry about mains supplies later.

An SMPSU works by chopping the input voltage and feeding this into an inductor, whose task is to store energy during the 'on' periods, then deliver it to a load during the 'off' periods. Inductors always 'try' to maintain the *current* flowing though them, whereas the *voltage across* the inductor can change as much and as fast as it wants. If a constant DC voltage is applied across an inductor the current though it will steadily rise according to the relationship V.t = I.L (t is seconds, L is inductance in henries). When the voltage is removed, the current tries to maintain itself and the resulting voltage flies up to as high as it needs to be to try to maintain that current. If the voltage is dissipated into something (energy is lost), the resulting current falls. If the circuit is just opened so 'no' current can flow in a loop, the voltage can be theoretically infinite, but in practice flies up to a sufficiently high value to lose itself either in a spark or be absorbed by inter winding capacitance or anywhere else it can be dissipated. It is this disconnect between off and on voltages across an inductor that is exploited in an SMPSU. We can see that provided the *average volt.seconds* across an inductor can be maintained at exactly zero, everything will be happy and a finite constant average current can then be allowed to flow in it.

Consider the 'buck'-SMPSU arrangement of **Figure 1**. When the switch is closed, the current in the inductor builds up, rising linearly according to the earlier equation. That current flows into the output smoothing capacitor and the load. When the switch is opened, current continues to flow in the same direction though the inductor, except that now it has to flow though the diode instead of the switch. The current is now falling; its rate of change has flipped, so the polarity of the voltage across the inductor flips, allowing the diode to keep the current flowing. If the switch is opened and closed at a regular rate, the rule that requires the average volt-seconds to be zero across the inductor means that during the on period, Ton, a voltage of Vin–Vout appears across the inductor and during the off period, Toff, that voltage is equal to (minus) Vout. So by switching with a square wave with unequal on and off times, in order to maintain the *average volt.seconds = zero* rule, this equation must hold: (Vin–Vout) * Ton = Vout * Toff With a bit of rearranging, we get the condition Vout = Vin * Ton / (Ton + Toff)

In other words Vout is proportional to Vin and the duty cycle of the switching waveform. If we monitor the output voltage and compare against a reference, the error signal can be used to adjust the duty cycle to maintain Vout constant. We have a stabilised step down SMPSU. Remember, the current flowing through the inductor is rising and falling continuously in order to maintain the on and off voltage imposed across it. Since this current forms the load current it must be smoothed. That is the job of the output capacitor. The output C is not part of the SMPSU process itself; its task is just to smooth the output and prevent the changing inductor current from passing though into the load itself.

The buck-mode converter shown can generate an output voltage that can only be lower than the input. **Figure 2** shows an

alternative arrangement called a 'boost-mode' converter that always generates a voltage higher than the input. During the switch on time, the inductor current builds up just as it did for the buck design. But now, when the switch is off, the current has to flow though the diode directly into the load and there is no upper limit to where that voltage can end up. Since it is in series with, and added to the input, Vout must be higher than Vin. If we continuously operate the switch at a constant rate we again force an *average* voltage across the inductor of zero, which is only possible if Vin * Ton = (Vout – Vin) * Toff or by rearranging Vout = Vin * (Ton + Toff) / Toff. Now the output capacitor has a harder task as it has to store the entire energy from the off period and deliver it to the load during Ton. Once again, by feeding back a divided down portion of the output, comparing it against a reference and using this to control the duty cycle of the PWM waveform, a constant stepped up output voltage can be generated. These two topologies form the basis of nearly all SMPSUs. Typical switching frequency in all modern SMPSUs is in the region 25 to 200kHz, with some advanced designs running even higher, even over 1MHz.

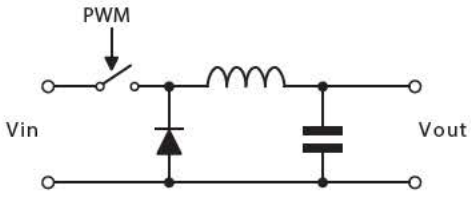

FIGURE 1: Buck mode (step down) SMPSU.

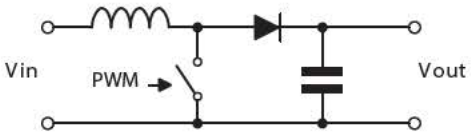

FIGURE 2: Boost mode (step up) SMPSU.

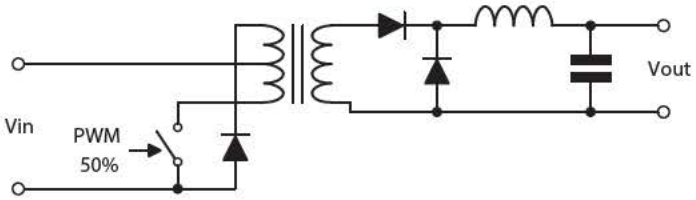

FIGURE 3: Buck mode controller with isolating transformer.

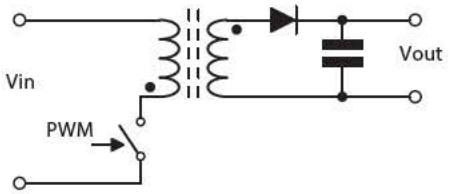

FIGURE 4: Boost controller with isolated inductor windings.

Isolated SMPSUs

What happens if we are not allowed a direct connection between input and output? Such is the case with all mains input SMPSUs, where we must have isolation from the mains input. The solution is to incorporate a transformer inside the module with isolated primary and secondary windings. As we are already switching the PSU at a high frequency, this transformer can be made of ferrite material, which makes it lightweight and small (even for SMPSUs delivering hundreds of watts). **Figure 3** shows a transformer built into a 'buck' converter. The right hand side has the traditional diode, inductor and capacitor arrangement seen before, but there is more than just a transformer here. The extra complexity comes-about as the zero mean volt. seconds rule applies equally to transformers as it does to inductors. So, bearing in mind we are supplying the transformer's primary with an arbitrary duty cycle input voltage, we must be able to 'reset' the core during the off period so its mean flux is always zero. Some of the flux is lost in transferring the energy into the secondary winding, and hence out, but there is plenty left. That is the task of the centre tapped winding and the input-side diode. Any residual flux left in the core when the switch is off causes current to flow out of the primary through this diode and back into the supply. When there is no output load all the input is returned to the supply and the SMPSU consumes nearly no power. Since the flux must be allowed to die completely before

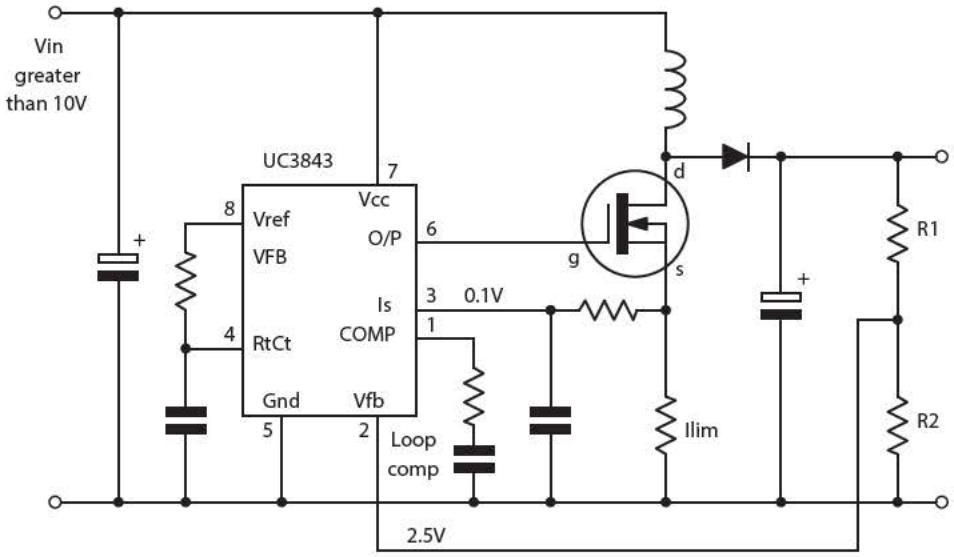

FIGURE 5: Circuitry around the UC3843 SMPSU controller chip.

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the switch is turned back on, the off period, Toff must be greater than Ton, or duty cycle must always be lower than 50%. While this would have been a major limitation in the simple supply of **Figure 1**, an additional transformer now gives us the luxury of also changing voltages by varying the primary / secondary turns ratio, Np / Ns. So now Vout = Vin * Ton / (Ton + Toff) * Ns / Np. With few turns of wire for the secondary output, this makes it ideal for transforming from the typical 320V DC input from rectified mains. Many SMPSU controller chips have options allowing a maximum 50% duty cycle to be forced.

Boost designs can also be used with isolated windings. This gives one of the more elegant and simplest SMPSU concepts. **Figure 4** shows the idea. The switching inductor itself is now made with primary and secondary windings, which opens up all sorts of possibilities as the voltages across the two windings follow the same ratio as they do in transformers. *Please note, though, it is NOT an actual transformer. Inductors and transformers have very different principles of operation.* We can have Ns lower than Np, giving an overall step down. The vast majority of small mains SMPSUs including 'wall-warts' work like this. Or we can make Ns much higher than Np, giving a step-up, and this way we can generate very high output voltages from a battery supply – many kilovolts if we want, provided a suitable high voltage diode and capacitors are used.

Regulation and feedback is made complicated with isolated designs by the need for that isolation. Many small PSUs provide an extra winding on the inductor whose rectified mean output is proportional to Vout, then feed this isolated voltage back to the controller. Another is to use a reference and comparator in the output side and feed the correction back through an opto isolator. This is done in bigger PSUs and many laptop supplies.

Controller chips

The variable duty cycle switching waveform and voltage feedback comparison is usually performed in a dedicated SMPSU controller chip that also directly drives MOSFET switches. There are hundreds of different types of such chips, but one of the simplest and easy to use in homebrew designs is the UC3842 to UC3845 family of 8 pin devices. **Figure 5** shows a simple non-isolated step up converter using the UC3843. Compare the components to Figure 2. In addition to that, there is built in current limiting by monitoring the average (smoothed) input current passing through the FET switch.

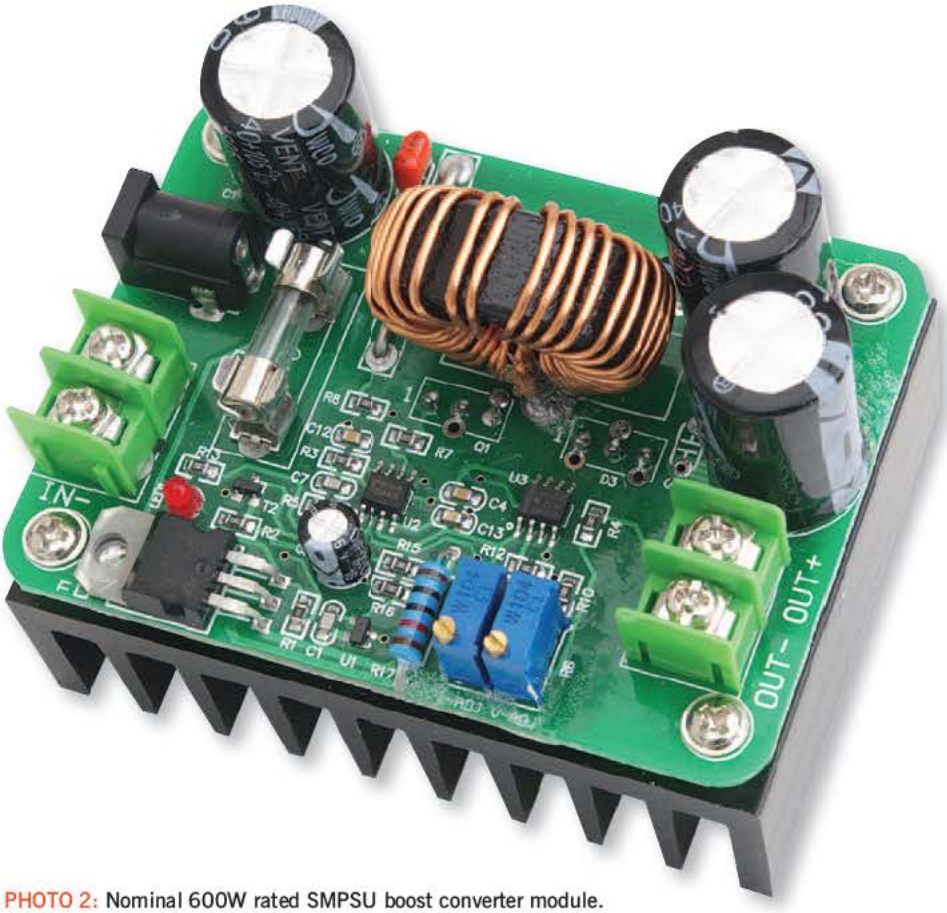

PHOTO 2: **Nominal 600W rated SMPSU boost converter module.**

A control system adjusts the duty cycle to ensure a potted-down version of the output (via R1 and R2) is equal to its internal 2.5V reference. Other components are used for loop stability compensation and for setting the basic oscillator frequency. For more details, including help on inductor selection and construction, see the data sheet. Most of the big catalogue suppliers stock this very popular chip series and they usually provide downloadable data sheets.

Ready made modules

Two non-isolated boost modules suited to a wide range of applications can be seen in **Photo 1** and **Photo 2**. These were obtained from eBay (search using the term 'boost SMPSU module'; they appear to be available from several suppliers). These ones are rated respectively for up to 150 and up to 600 watts. There is a bit of advertising licence here as those power throughputs are only possible towards the maximum rated input voltage. But even so, they seem very capable.

Both modules use the UC3843 chip, with the small module rated for 10 to 35V input and up to 35V output with a maximum input current of 10A. The large one is rated for 10-60V input, up to 80V output and 16A input current. After delivering 28V at 3A for 20 minutes, the smaller one was only running comfortably warm to touch. I had no load sufficient to test the high power one properly.

One example of usage could be for supplying a constant 13.8V from lead acid batteries as they discharge from 13V to 10V. Another, generating a 28V or 50V supply from a nominal 12V input for medium to high power RF PA stages. In this latter application, as the SMPSU module uses a well-known chip type we can get at the voltage feedback control circuitry for our own purposes. How about monitoring reflected RF from the antenna and using it to reduce the PA voltage to protect the device against poor match? Or automatically adjusting PA volts to a linear power amplifier with mean drive level to optimise efficiency and battery life? Or replace the inductor with a dual winding one to make a high voltage PSU for valve equipment?

EMC and filtering

Now we have seen how SMPSUs work, we should have enough insight and inside knowledge to see how they can be made clean and spurious free, and useable. More on that next time.

Design Notes

SMPSU filtering and EMC

Last time we looked at SMPSUs, how they chop up a DC input voltage with a variable duty cycle switch then use an inductor to store and transfer energy to the output, which is then cleaned up with a capacitor. A transformer can be included if isolation is required, or it may come from separate windings on the inductor. The switching is typically performed somewhere in the region 50kHz to several hundred kilohertz and for maximum efficiency the switch has to transition rapidly. Any time wasted in the crossover will end up with energy being dissipated in the switch, with lower efficiency and high device dissipation. The switching is almost invariably done nowadays with a power MOSFET, allowing switching times of a few hundreds or even tens of nanoseconds. Such fast switching is bound to lead to the possibility of high frequency interference at harmonics of the PWM rate. *[See the EMC column on page 40 for more on this subject – Ed].*

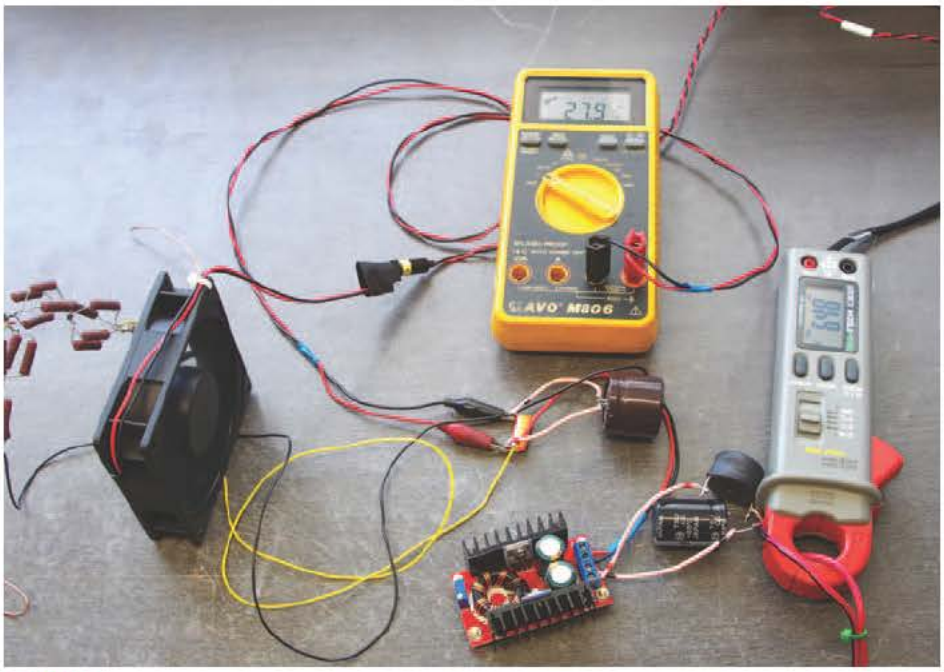

PHOTO 1: Breadboard setup for testing the 12 28V converter, and determining additional filter components needed.

In designing the SMPSU module, all paths around the switching device, inductor and input source need to be made as short as possible and of thick, low inductance conductors. **Photo 1** shows a test setup used for the eBay 150W module described last time, with additional input and output filter components that we'll now discuss. The output power is dissipated in the fan-cooled wirewound resistors on the left hand side.

There are two main paths by which the switching transients can be conducted to the outside world: via the input circuitry and via the output circuitry. The input voltage is being chopped so the input current is alternating between some high value and zero. The diagrams last month deliberately showed the switch operating directly on the input voltage supply to emphasise its operation. In practice that supply cannot be a perfect zero-impedance voltage source and will also quite likely be delivered along some lengths of conductor with their own (hopefully small) resistance. So those pulses of current will always have to be augmented by an input capacitor. The capacitor will always be there on the module and form part of the short, low inductance loop just described. But this alone is not sufficient. Electrolytic capacitors cannot be perfect and there will always be some residual series resistance and inductance, so they can never completely smooth out the input.

Photo 2 shows an oscilloscope trace at the input to the 12 to 28V boost mode converter when delivering about 70W to a load with none of the external filter components of Photo 1 present, ie a direct connection. The 12V supply comes via about 2m of cable with 6mm² conductors

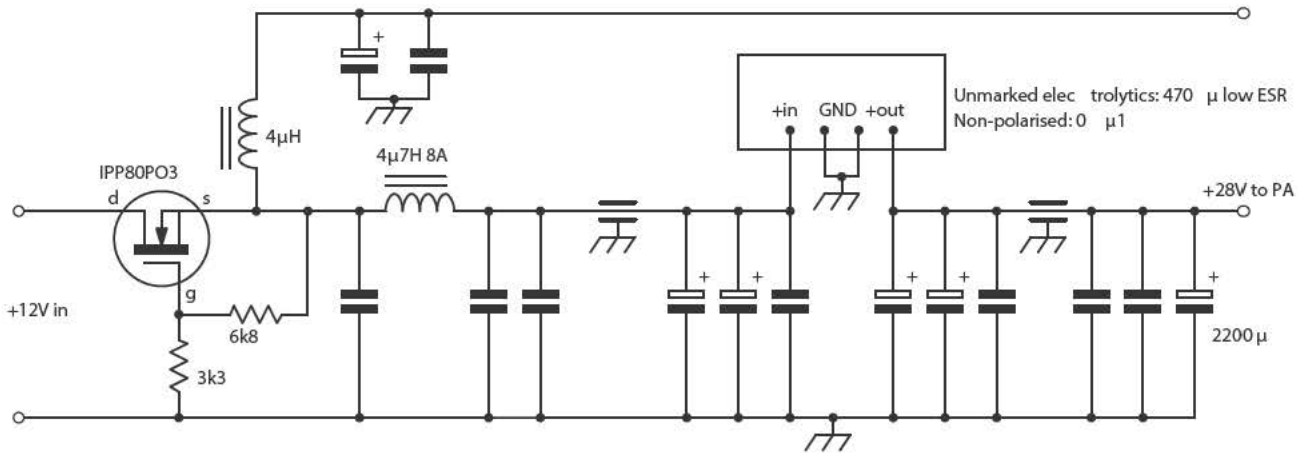

FIGURE 1: Circuit diagram of SMPSU input and output filtering and power conditioning for a 12 to 28V converter used in a 1296MHz transverter.

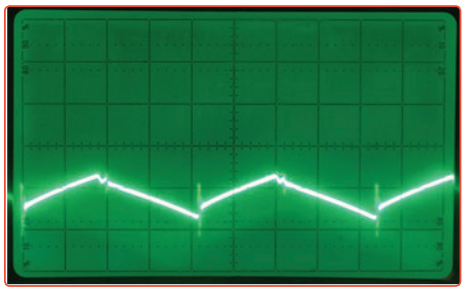

PHOTO 2: Input voltage at the terminals of SMPSU module with no extra filtering. Scale 5µs / 200mV per division.

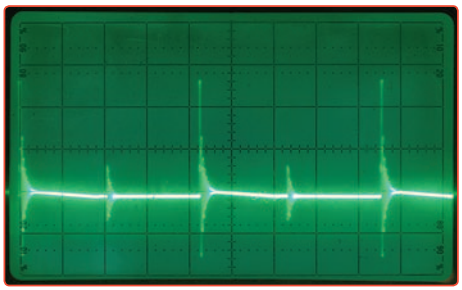

PHOTO 3: Output waveform with no additional filtering components. Scale 5µs / 2V per div.

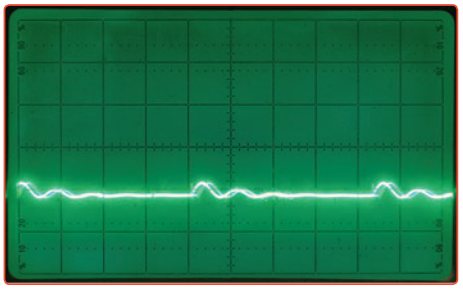

PHOTO 4: Output waveform with 330nF capacitor added. Scale 5µs / 2V per div.

from a bench PSU. The triangular waveform of about 200mV peak-peak is measured directly on the input terminals and is a direct result of the imperfect single input electrolytic on the module passing some of the pulsed current back to the input supply.

Note the high frequency ringing on the edges of the switching waveform. It is these that cause the RF interference, the bane of SMPSUs in radio applications. The triangular voltage variation causes less interference in its own right, unless it gets into low power stages elsewhere. To clean it up, two additional components can be added to the input circuitry, shown on the lower right of Photo 1, adjacent to the clamp ammeter. Adding extra high value electrolytic capacitors directly across the input terminals on its own effects only a minor improvement and does not solve the high frequency ringing passing out to the supply wires, from where is can be radiated. The best way to solve that is to first insert a choke. That is the black cylindrical unit, a 4µH 10A rated inductor taken from a scrap computer type PSU. Another 2200µF electrolytic is then added on the input to complete the filtering. Connecting the scope across the input now showed the ripple had reduced to a level that couldn't be seen on the scope. Some high frequency transients of a few tens of millivolts were still visible, but as they were also showing up when the scope probe wasn't even connected to the circuitry under test – I just had to accept they were being conducted in via common loops elsewhere in the test setup. No-one said this test layout was good!

Now we turn to the output. **Photo 3** shows the output waveform with no additional filtering. While there is less output ripple, a few tens of millivolts, the switching transients are horrible –they're many volts in amplitude. The main reason for this is that the switching FET on a boost SMPSU is directly connected to the output via the diode – the inductor is not there to smooth transients like it does at the input. Just adding a 330nF capacitor across the output (the 'Liquorice Allsort' type seen in Photo 1) reduced the transient, shown in **Photo 4**, to about 400mV amplitude, with its high frequency components removed completely. Adding another 1000µF electrolytic across the output reduced this to just a few tens of mV residual ringing which, again, I couldn't be certain wasn't stray pickup onto the oscilloscope though common grounding paths.

A practical solution

Depending on the SMPSU topology, the switching device has a more direct connection to one side or the other without the SMPSU inductor itself helping to smooth out HF transients. On boost mode converters – step up or low power mains ones – this is the output port so high frequency transients are more likely to appear there. On buck mode converters – step down or high power mains – the switching FETs are closer to the input and filtering should be concentrated here first. On large mains SMPSUs, this means good quality mains filter components.

The breadboard layout shown in Photo 1 is by no means an optimum setup, with long wires between decoupling components and no real attempt made to decouple high frequencies. **Photo 5** shows this same module integrated into a 'proper' filtering system, ready to be built into a 1296MHz transverter and 45W power amplifier. The circuit is shown in **Figure 1**. The input and output filtering components already discussed are included, along with many 100nF SMT capacitors sprinkled throughout and a couple of filtercons **[1]** added to clean up any VHF conducted interference.

Separate filtering is included for a 12V output to low level stages, preventing the input ripple from passing though to them. No residual ripple could be seen on this filtered line. The P-channel MOSFET on the input is for reverse polarity protection, as described in March 2016 *Design Notes*. The two resistors on the gate are used to keep the gate voltage down to about 9V in normal operation since the data sheet specifies a maximum value for this very low $R_{DS(on)}$ device of only 15V.

More on MOSFETs used for power switching

Robin Washington, M1REW sent in this note after reading the December 2016 Design Notes.

"I recently designed a ground power unit for my light aircraft and needed a very low turn-on resistance with a rating of 13.5V at 30A. I also needed to be able to turn it off, so after a lot of thought and reading my old MOSFET notes I realised that the drain to source junction is not a diode [as in a bipolar]. The diode is, as you say, parasitic and the power FETs will conduct in reverse. I tested this and obtained 0.016Ω across the two devices wired as you have them in [December 2016] Figure 4. They will conduct in either direction and will turn off. The parasitic diode is not conducting, as evidenced by the millivolt drop at 30A."

So the AC switch is even better than I thought!

All power FETs are *not* created equal. Look at the three P-Channel devices shown in **Photo 6**. Although made by different manufacturers, they all have roughly the same channel characteristics, a voltage rating of 20-30V and an on-resistance of 3.5 to 4 milli-ohms. But that is where similarity ends. The TO220 mounting of the first device allows a great deal of heat to be removed into a heatsink and high power operation is possible. But the internal bond wires, necessary in this rather large package type, add to the on resistance and give it the highest of the three. However, at such a high power rating and this $R_{DS(ON)}$ it could happily carry its rated 80A maximum with only about 30W dissipation.

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PHOTO 5: 12 28V SMPSU module with additional filtering components integrated onto a PCB. There is also a low power 12V output with extra filtering and P channel MOSFET input polarity protection.

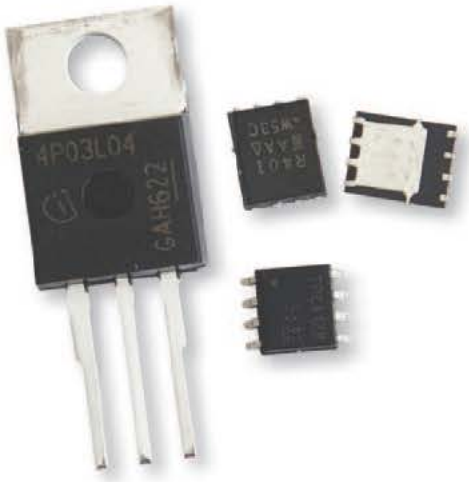

PHOTO 6: Three power MOSFETs, all with similar channel characteristics but very different packaging. Left to right, ICP80P03 TO 220 package, 30V 80A, $R_{DS(ON)}$ 4.1mΩ, 137W dissipation; TPC8128 SOIC 8 package, 30V 16A, $R_{DS(ON)}$ 3.9mΩ, 1.9W and SiR401DP SO8 package (seen from top and bottom), 20V 50A, $R_{DS(ON)}$ 3.5mΩ, 39W dissipation.

The tiny 8 pin SOIC package has no heatsinking capability worth speaking of, hence its 1.9W rating. This device is mainly designed for sitting inside lithium batteries, providing overload and discharge protection in conjunction with supervisory circuitry. Again, bonds to the 8 tabs add slightly to the channel resistance. At this low power rating its maximum current of around 16A gives a dissipation not far from its rating.

The most interesting of the three is the even smaller SO8 packaged device. This has a 'Pin 0', a tab on the underside for direct soldering to a copper PCB plane (then through to a heatsink). With this construction there would be no internal bond wires, the internal tracks coming direct to the external tab, so it has the lowest $R_{DS(ON)}$ of them all and a decent power dissipation capability due to the heatsinking possibilities. Assuming the channel resistance is maintained, at the maximum current rating of 50A continuous it is dissipating a mere 9W – well below its rated maximum.

The one thing to be wary of for all these is the gate voltage, which is lowest for the SiR (SO8 package) device at 12V. However, the switching threshold is a lot lower so a couple of resistors to keep it to a safe value as shown in Figure 1 can be used with 13.8V supplies that could go to, perhaps, as high as 15V.

All the P-channel FETs shown and many similar, as well as ones suitable for 28 and 50V supply switching, are available from Farnell and other catalogue suppliers.

Log power detectors

After seeing the May 2015 issue on log power detector chips Chris, G8BKE, sent in details of the AD8318 device, which is rated for operation up to 6GHz. See [2] for more details of a power meter module using this device.

Websearch

[1] 'Filtercons' are a feedthrough like device that have a ferrite loaded middle as well as capacitance, so they form a low pass filter. A small black and silver coloured one can just be glimpsed in Photo 5 to the bottom right of the inductor. The device in the foreground is a standard ferrite device with no integral capacitance.

[2] AD8318 Log Detector Module www.sv1afn.com/ad8318.html

Amateur radio on the International Space Station continued from page 33

Finally, at a meeting in Lucerne, Switzerland, on 2 December 2016, ESA's twenty-two member states approved a commitment to extend European participation in the ISS programme to 2024. The ARISS adventure is far from over, and that we can look forward to at least seven more years of experimentation and educational contacts with schools.

Websearch

NASA ISS pages: www.nasa.gov/mission pages/station/main/index.html
Online tracking of the ISS and amateur satellites: http://heavens above.com
ARISS main website: http://ariss.org
Satellite tracking software: www.amsat.org/amsat new/tools/software.php
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